

Very Long Baseline Interferometry as a tool to probe the solar corona

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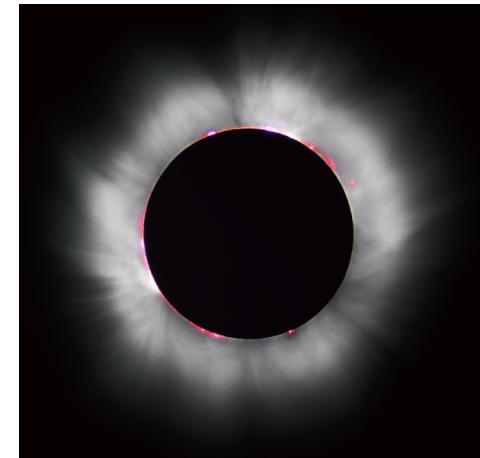
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Introduction

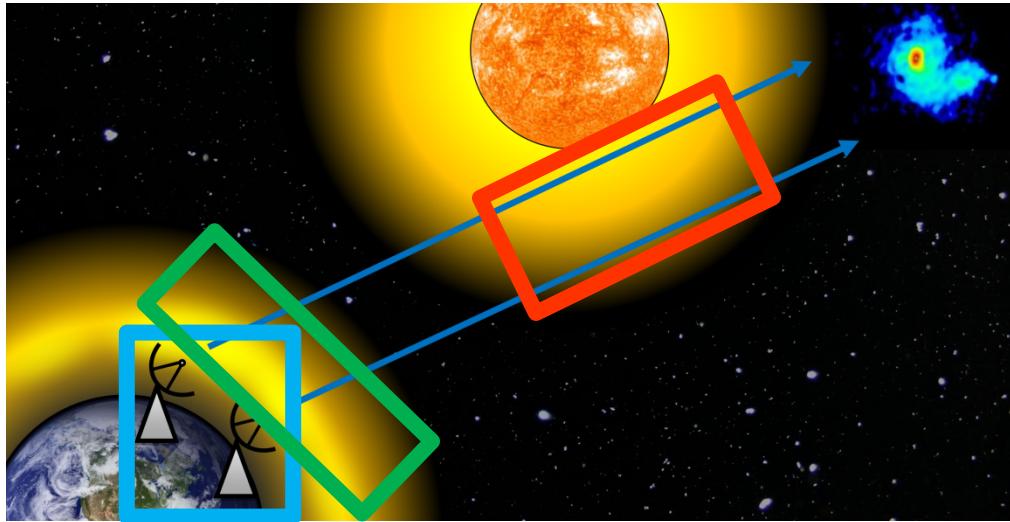
- Sun corona: the Sun's atmosphere
- Impact on radio signals dependent on electron density
- Power-law model for electron density

$$N_e(r) = N_0 r^{-\beta}$$

- In the past from spacecraft tracking
- Soja et al., 2014: for the first time from VLBI
- This talk: major improvement of VLBI estimates
- Motivation: improve understanding of solar physics & models, monitoring of solar activity & space weather



Observation Principle



$$\tau_{disp,x} = \frac{40.3}{cf_x^2} (\Delta STEC_{corona} + \Delta STEC_{iono}) + \tau_{inst}$$

$$STEC = \int_S N_e ds \approx \sum_S N_e \Delta s$$
$$N_e(r) = N_0 r^{-\beta}$$

$$STEC = mf \cdot VTEC'$$

Previous VLBI results

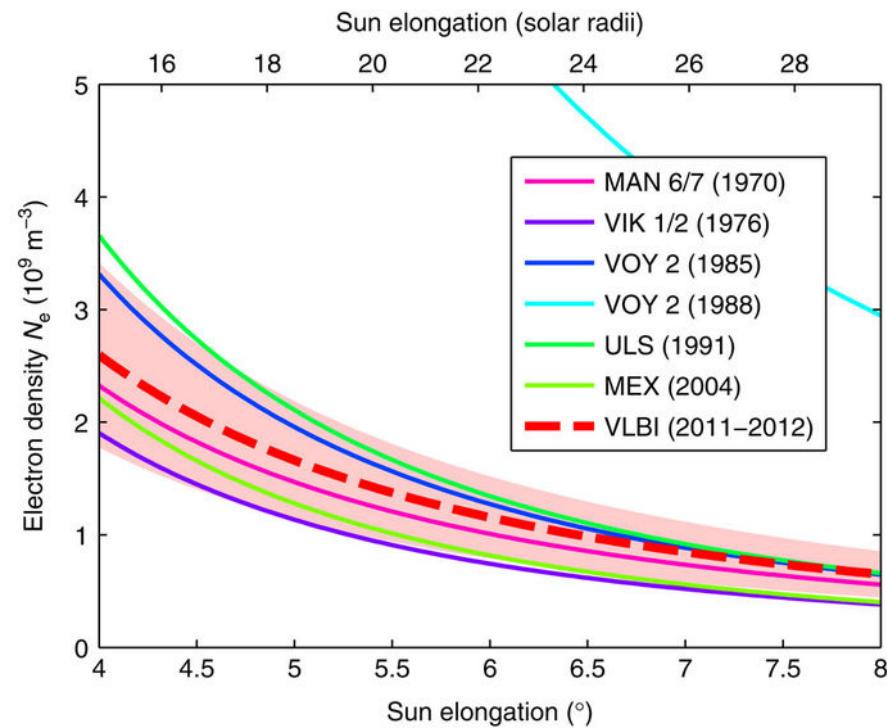
Probing the solar corona with very long baseline interferometry

B. Soja, R. Heinkelmann & H. Schuh 

- Twelve IVS R&D sessions in 2011/2012
- Observations with minimum solar elongation of about 4°
- Power-law $N_e(r) = N_0 r^{-\beta}$
- Correlation between N_0 and β
→ only N_0 could be estimated

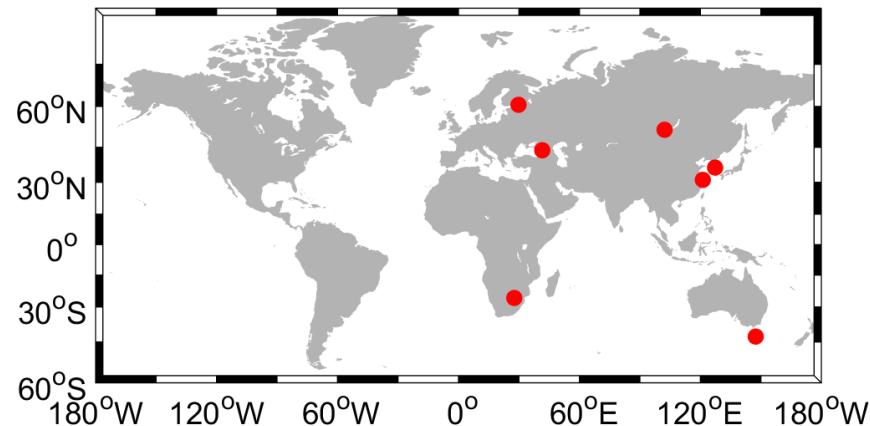
$$N_0 = (0.57 \pm 0.18) 10^{12} \text{ m}^{-3}$$

for $\beta := 2$



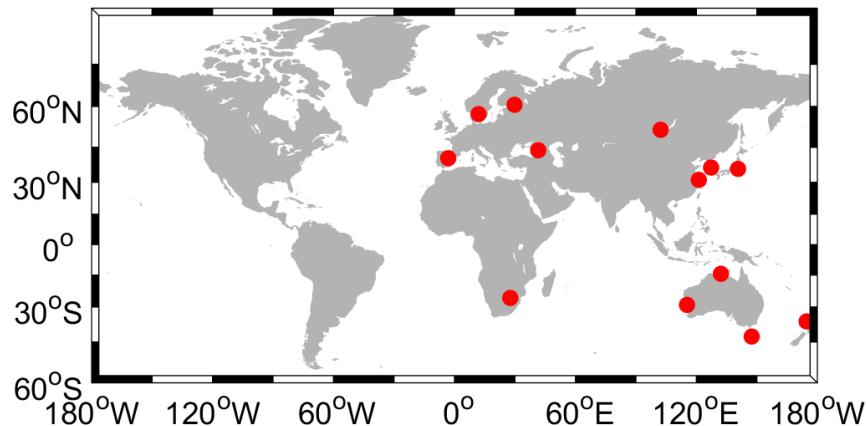
New VLBI data – session AUA020

- AUSTRAL session on May 1-2, 2017
- 24-hour experiment with 7 radio telescopes
Bd-Hh-Ho-Kv-Sh-Sv-Zc
- Goal: test general relativity → observations close to the Sun
 - 0235+164 with 452 observations at 1.2–1.5° elongation
 - 0229+131 with 577 observations at 2.2–2.7° elongation
- Reduce thermal noise from Sun:
 - Strong radio sources
 - Telescopes with large dishes
 - 1 Gbps data recording rate

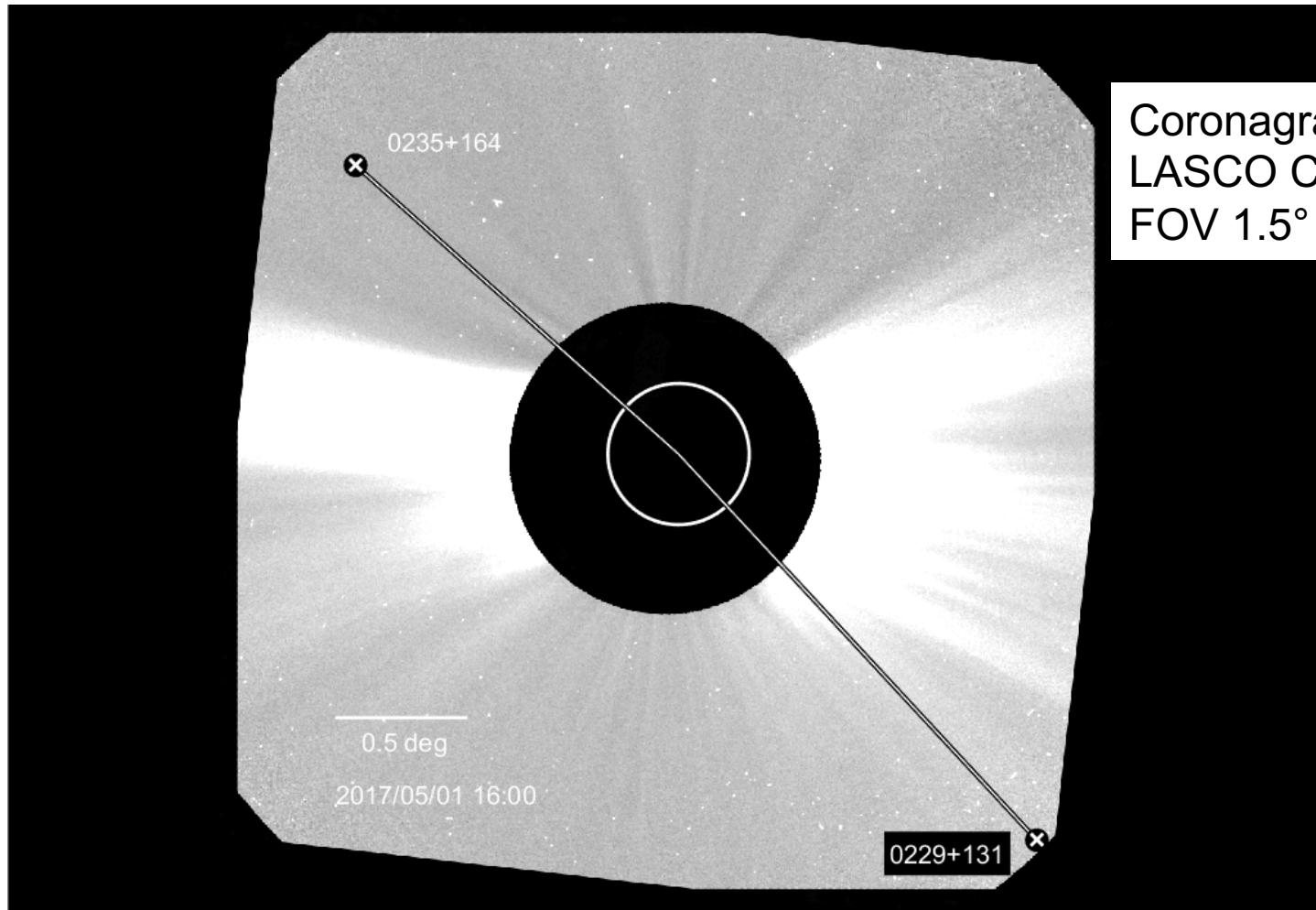


New VLBI data – session AUA029

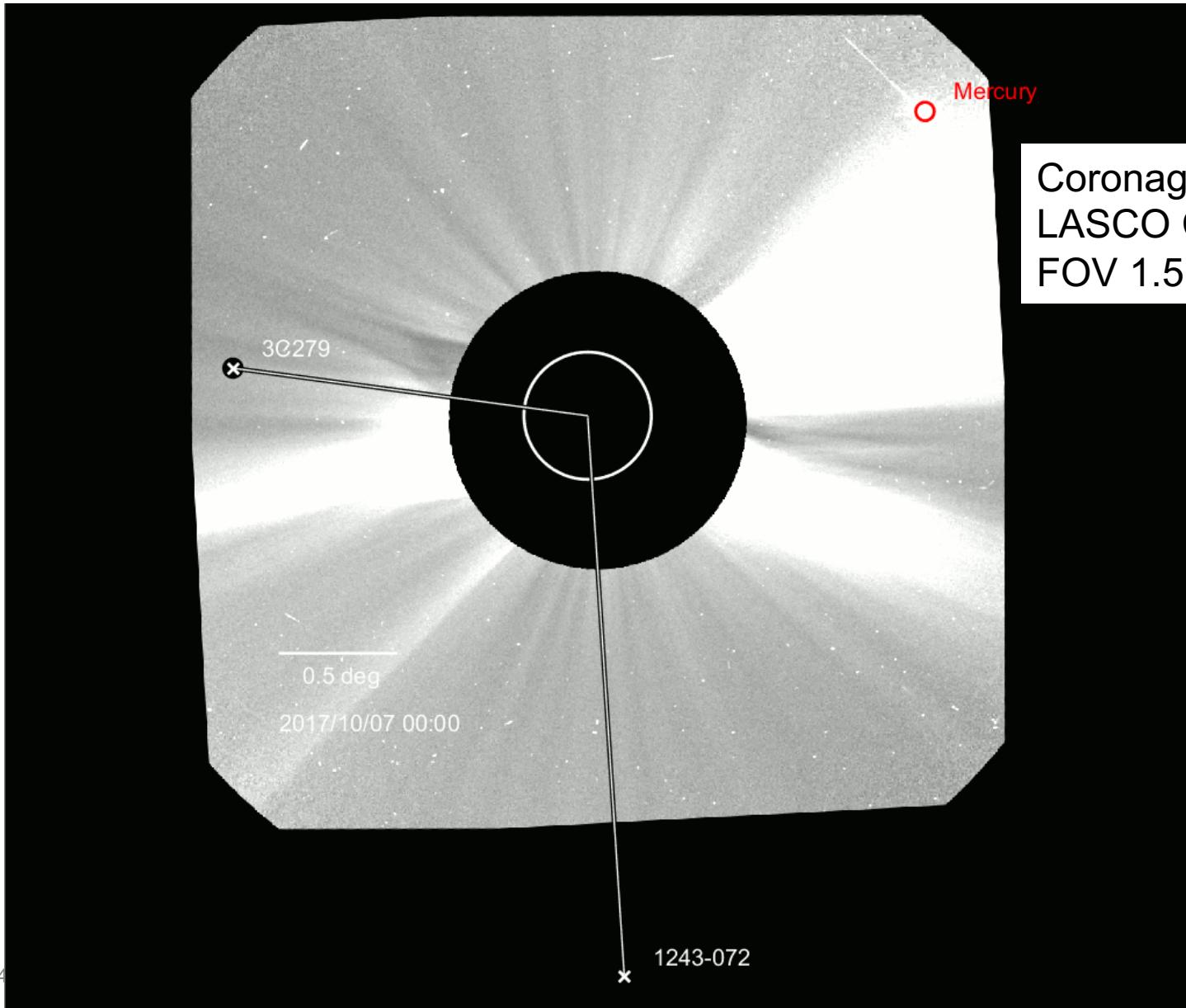
- AUSTRAL session on Oct 7, 2017
- 24-hour experiment with 13 radio telescopes
 - Bd-Ho-Ht-Kb-Ke-Kv-On-Sh-Sv-Ww-Yg-Ys-Zc
- Goal: test general relativity → observations close to the Sun
 - 3C279 with 2775 observations at 0.5–1.5° elongation
 - 1243-072 with 9 observations at 2.3–2.6° elongation
- Reduce thermal noise from Sun:
 - Strong radio sources
 - Telescopes with large dishes
 - 1 Gbps data recording rate



Observation geometry – AUA020



Observation geometry – AUA029



New VLBI results – AUA020

- Only estimating N_0 :

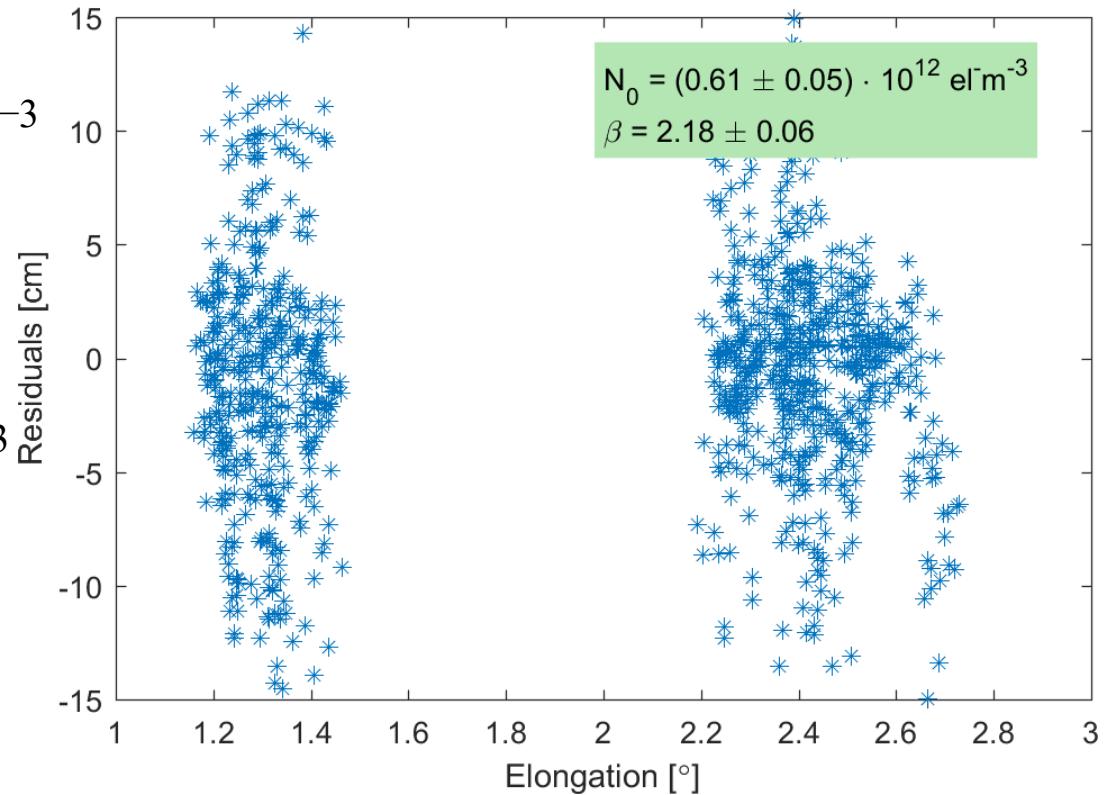
$$N_0 = (0.48 \pm 0.007) 10^{12} \text{ m}^{-3}$$

$$\beta := 2$$

- Estimating N_0 & β :

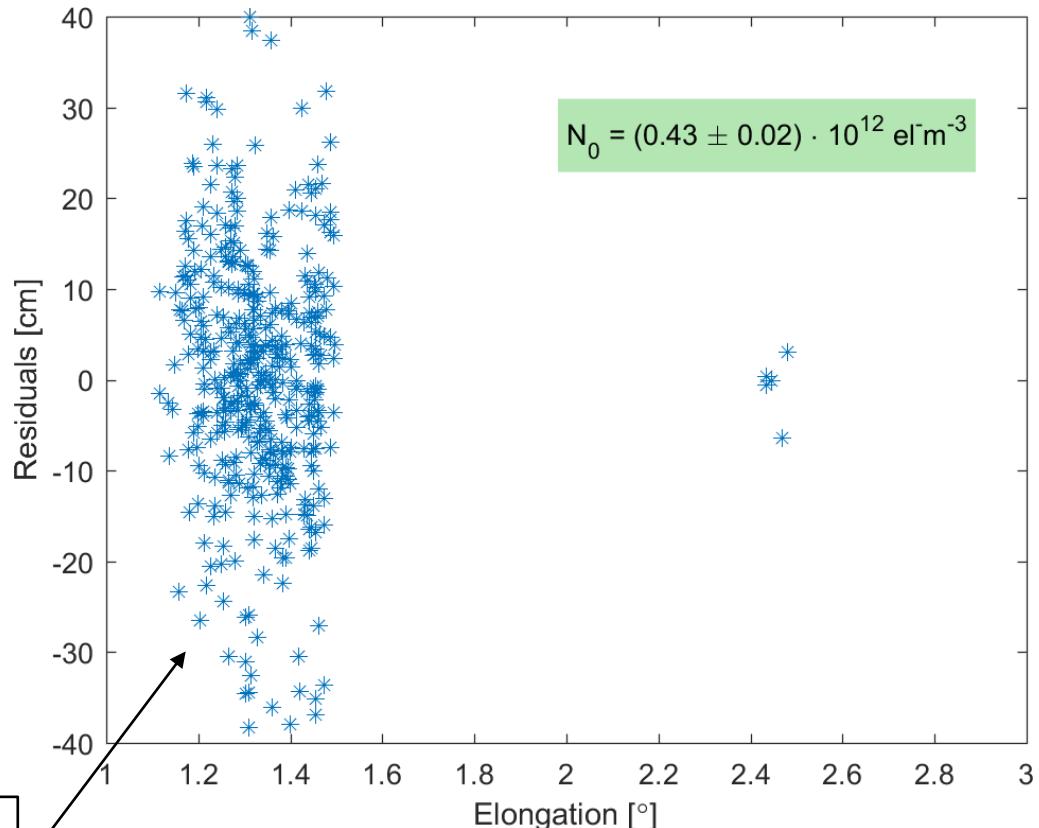
$$N_0 = (0.61 \pm 0.05) 10^{12} \text{ m}^{-3}$$

$$\beta = 2.18 \pm 0.06$$



New VLBI results – AUA029

- Only estimating N_0 :
 $N_0 = (0.43 \pm 0.02) \cdot 10^{12} \text{ m}^{-3}$
 $\beta := 2$
- Estimating N_0 & β



417 out of 2775 observations
remaining after outlier elimination

Comparison to previous VLBI results

R&D sessions (2011/2012)	$N_0 = (0.57 \pm 0.18) 10^{12} \text{ m}^{-3}$
AUA020 (05/2017)	$N_0 = (0.48 \pm 0.007) 10^{12} \text{ m}^{-3}$
AUA029 (10/2017)	$N_0 = (0.43 \pm 0.025) 10^{12} \text{ m}^{-3}$

$\beta := 2$

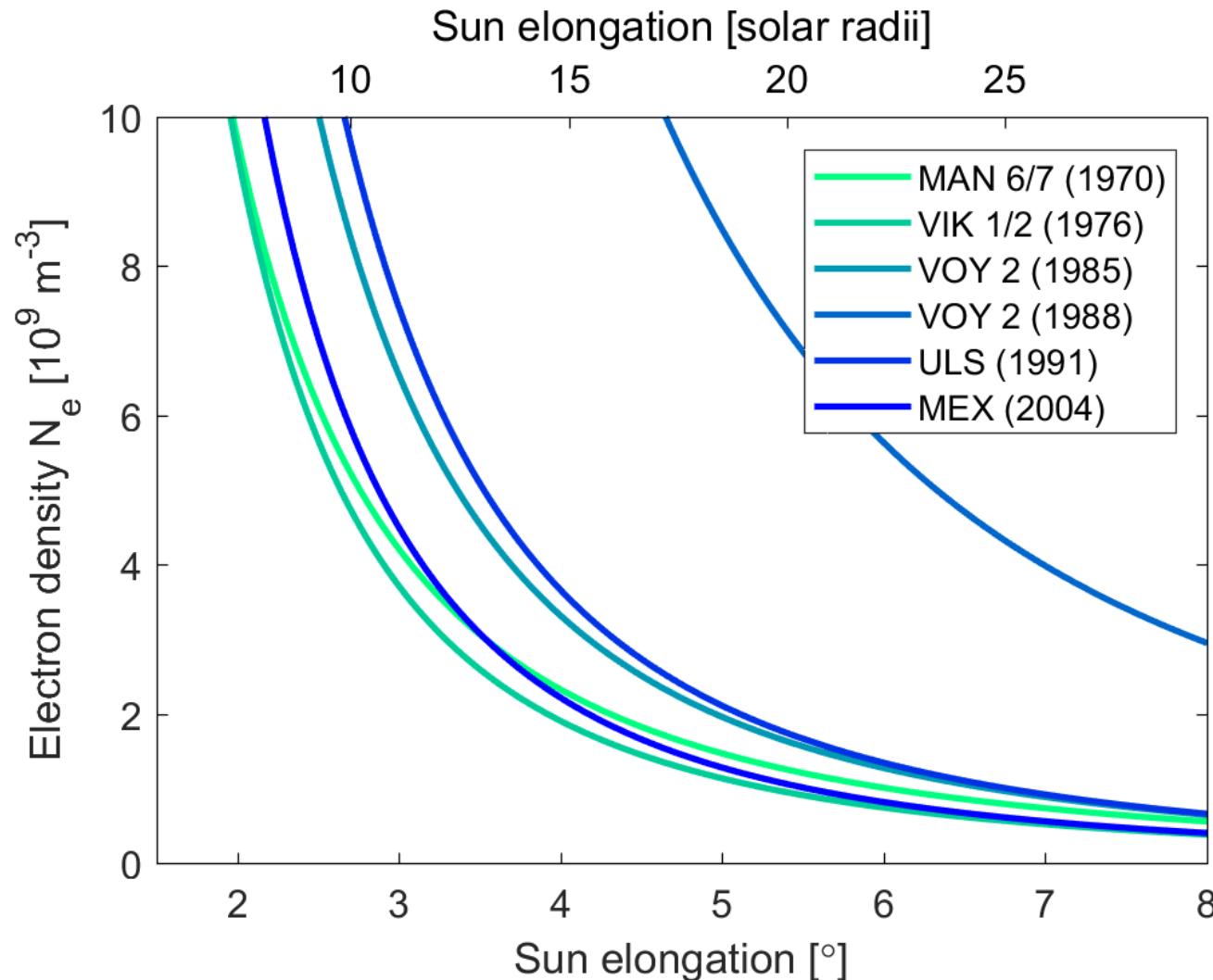
- Formal error 25x smaller for AUA020 compared to R&D
- AUA020 and AUA029 agree within 2σ
- Lower electron density during 2017 related to lower activity
 - Sunspot number (SSN)
 - Average during 2011/2012: 58
 - AUA020: 12
 - AUA029: 11

Comparison to spacecraft tracking I

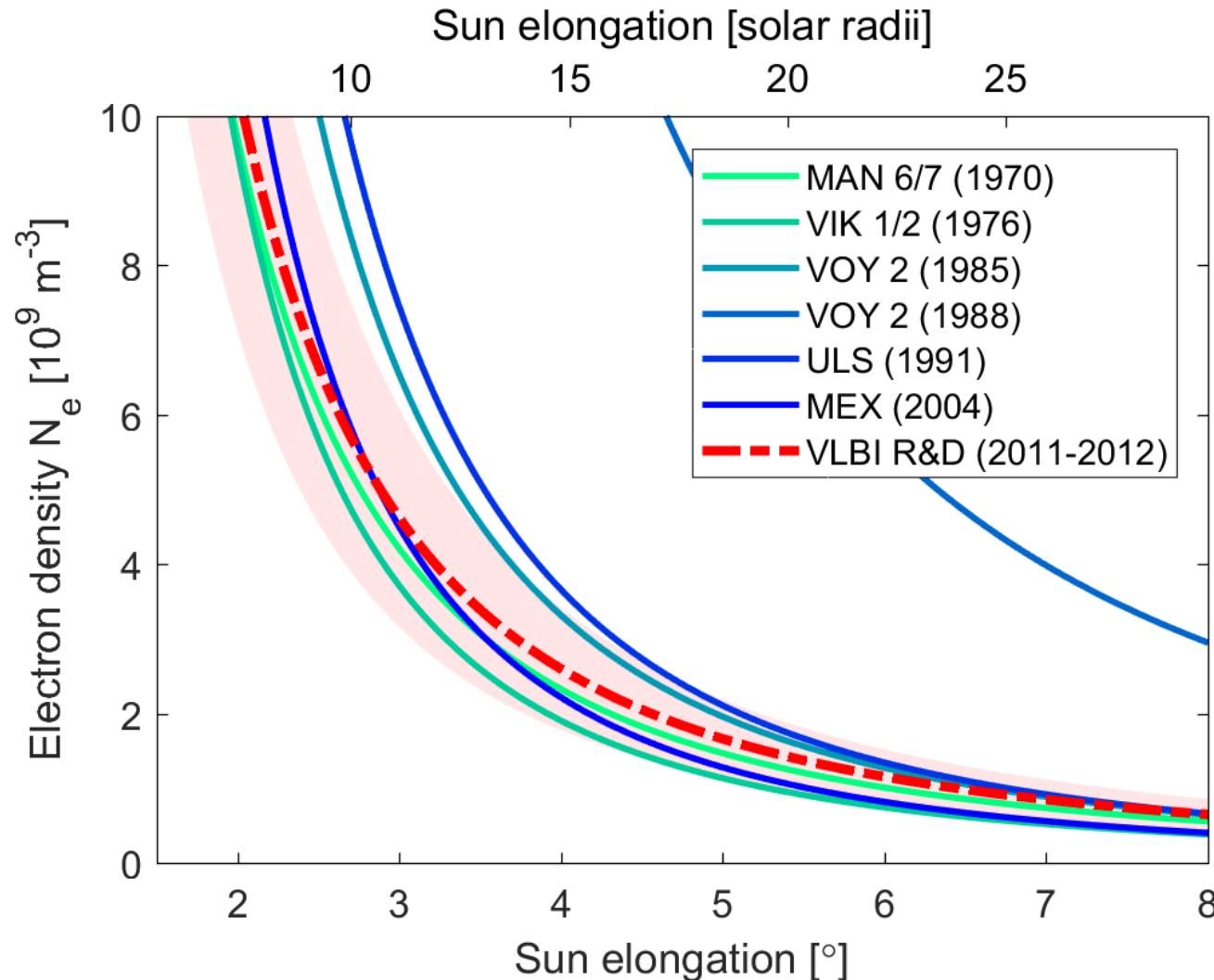
[Bird et al., 2012]

Mission / Data set	Year	Min. Elongation	N_0 [10 ¹² m ⁻³]	β	$N_e(20 R_s)$ [10 ⁹ m ⁻³]	SSN
MAN 6/7	1970	1.6°	0.60	2.06	1.25	105
VIK 1/2	1976	0.8°	0.99	2.32	0.95	13
VOY 2	1985	1.7°	1.92	2.36	1.63	18
VOY 2	1988	1.4°	6.04	2.25	7.14	100
ULS	1991	1.4°	2.85	2.47	1.74	145
MEX	2004	1.0°	1.68	2.46	1.06	40
ROS	2006	2.2°	0.84	2.14	1.38	15
MEX	2008	2.5°	0.49	2.07	0.99	3
VLBI R&D	2011/12	3.9°	0.57	2.00	1.43	58
VLBI AUA020	05/2017	1.2°	0.61	2.18	0.89	12
VLBI AUA029	10/2017	1.1°	0.43	2.00	1.08	11

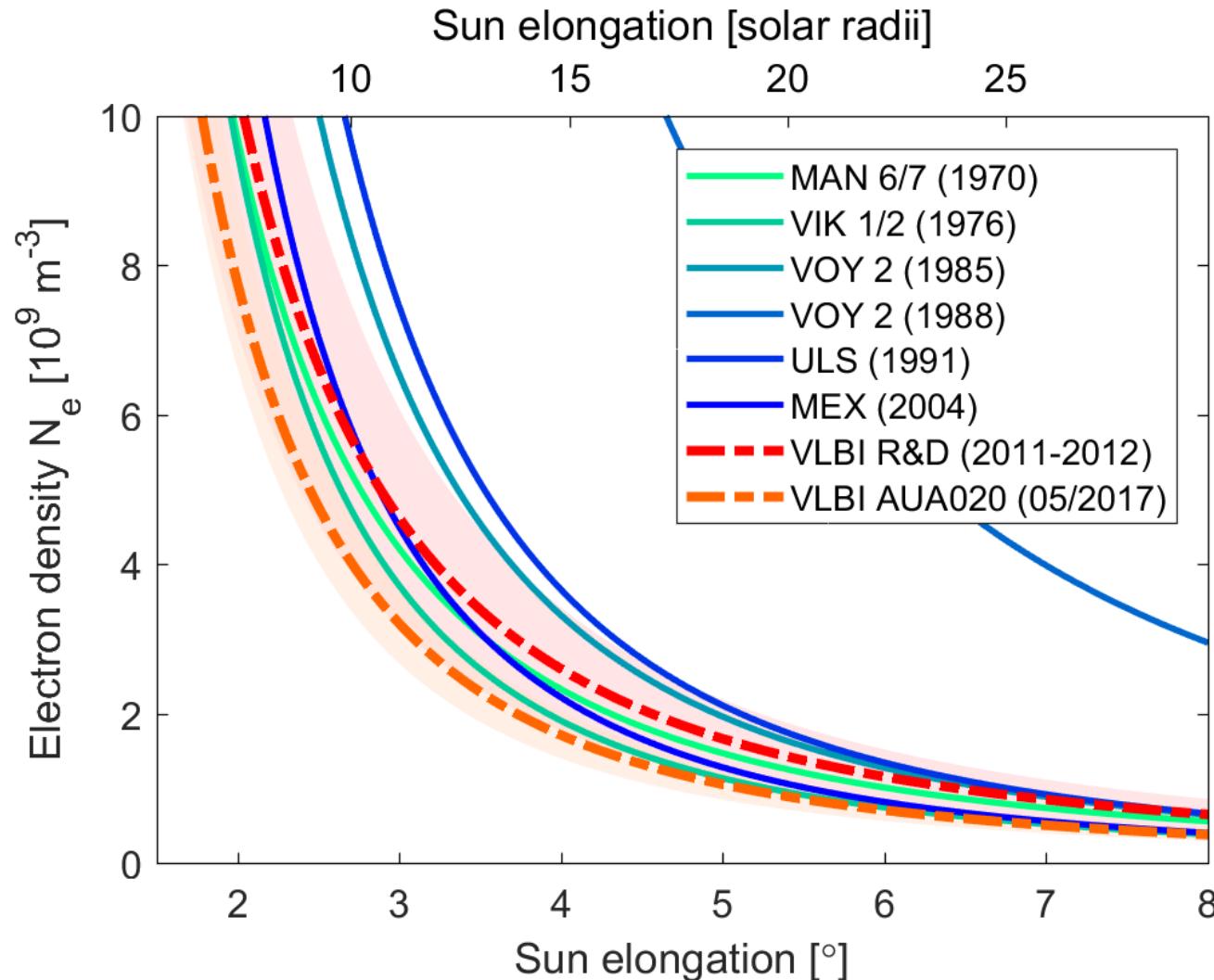
Comparison to spacecraft tracking II



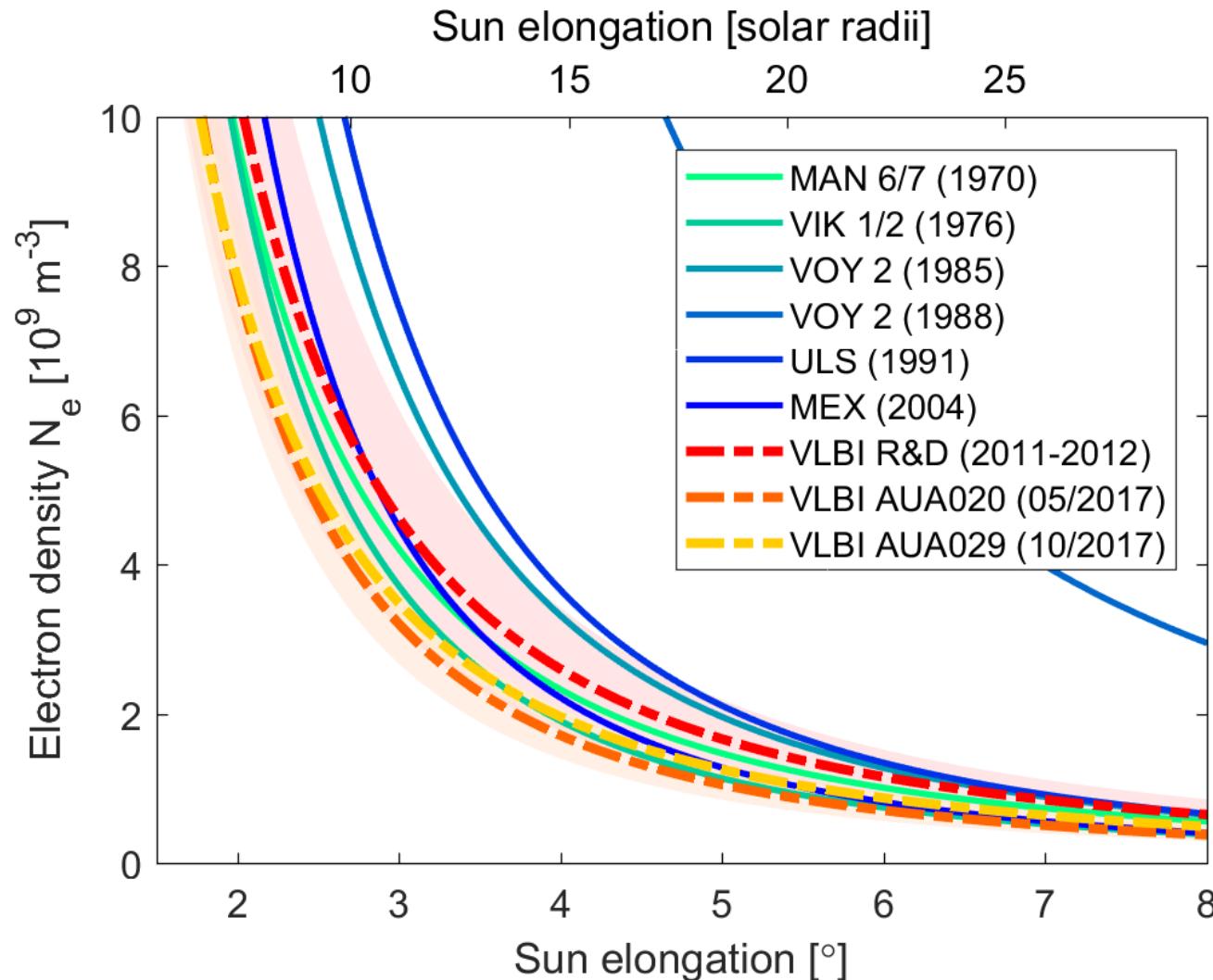
Comparison to spacecraft tracking II



Comparison to spacecraft tracking II



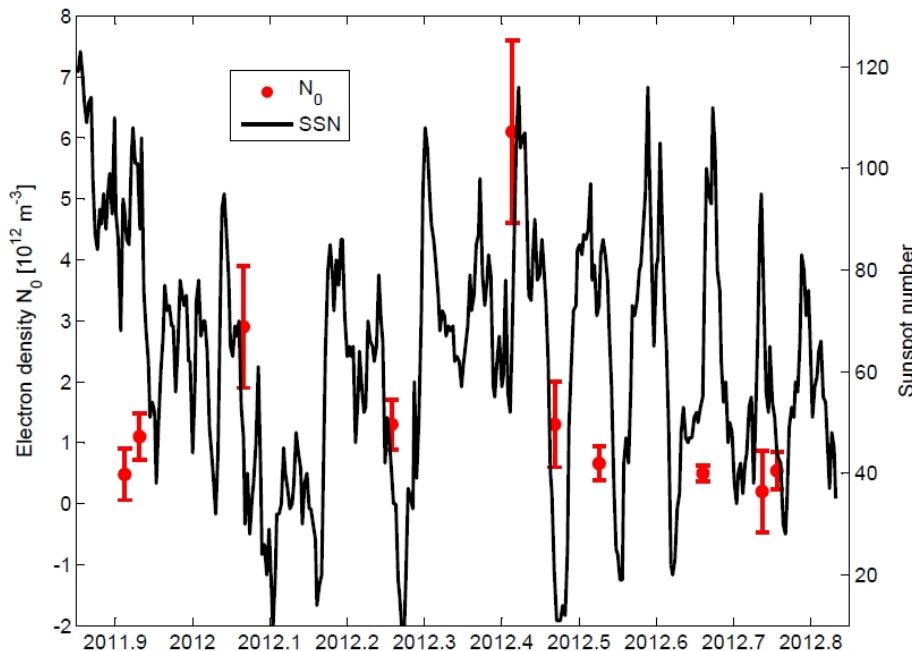
Comparison to spacecraft tracking II



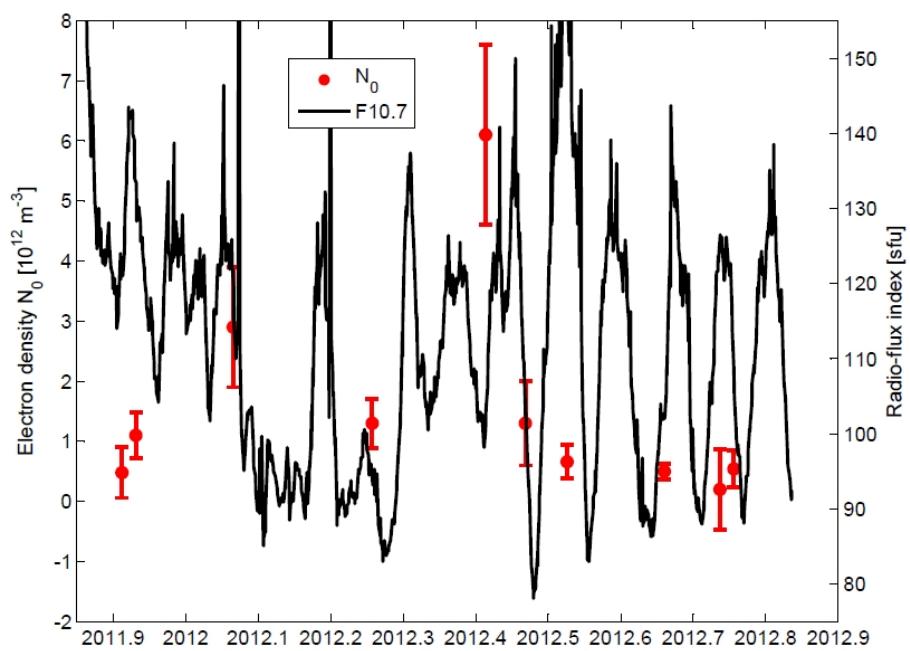
Comparison: electron density & solar activity

R&D sessions (2011/2012)

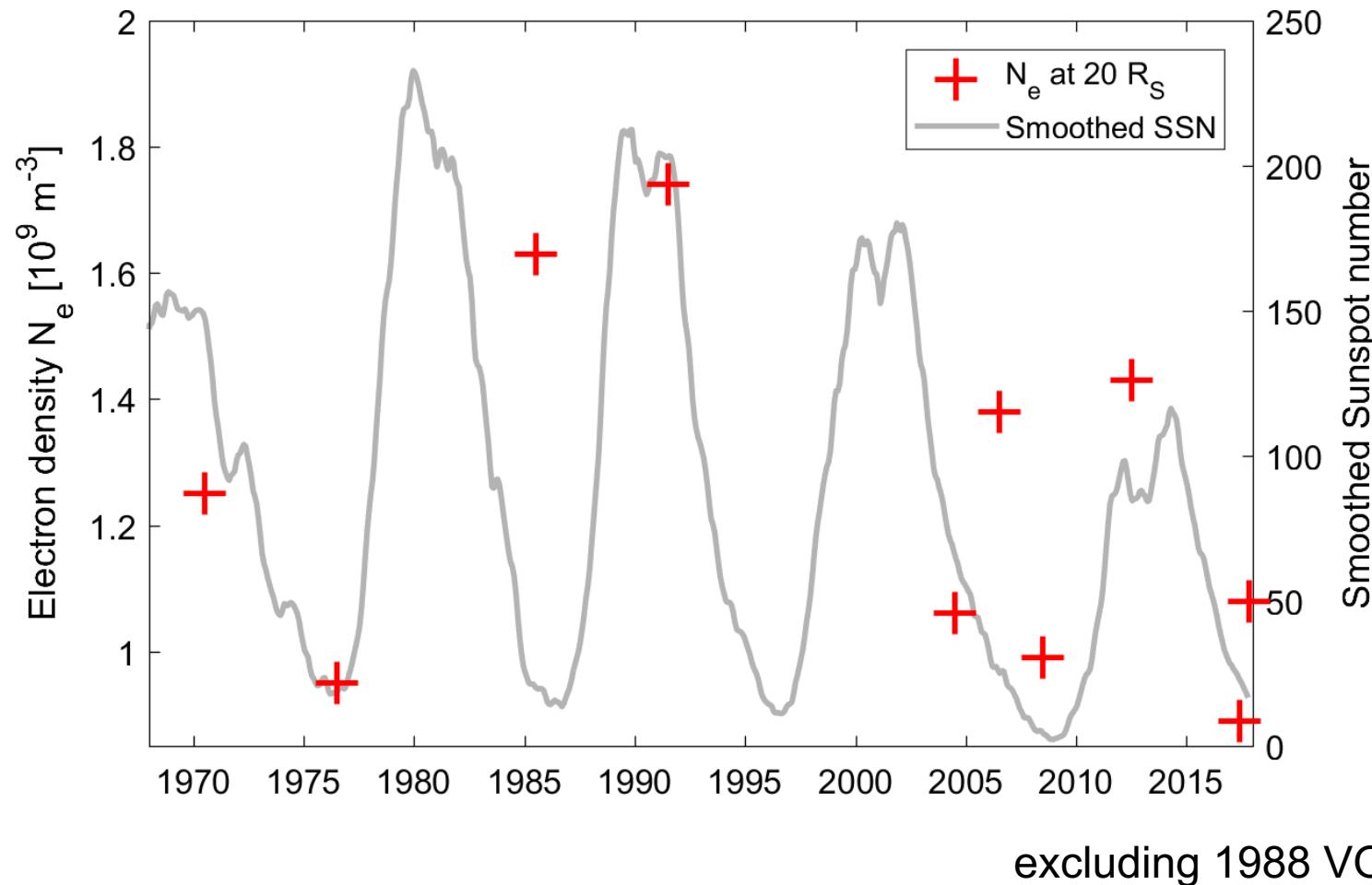
Relative Sun spot numbers (SSN)



Radio-flux index at 10.7 cm (F10.7)



Comparison to Sunspot numbers



Conclusions

- **Successful** VLBI observations at 1° solar elongation due to high sensitivity and (mostly) favorable solar conditions
 - Observations at 0.5° solar elongation in active regions
- Major **improvement** in the **precision** of **solar corona** electron densities from VLBI (up to 25x)
- First determination of **both power-law parameters** N_0 & β
 - 2+ radio sources close to the Sun needed
- **Good agreement** with existing models
- Success depends on solar activity in observed regions → great potential for real-time scheduling!



Thanks for your attention!

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